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ELECTRON DENSITIES IN A SOLAR FLARE DERIVED FROM X-RAY SPECTRA.(U)
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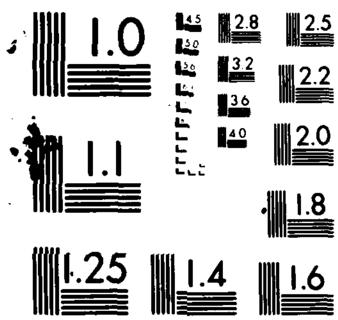

MICROCOPY RESOLUTION TEST CHART
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Prepared for

SPACE DIVISION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, Calif. 90009

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-81-C-0082 with the Space Division, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for The Aerospace Corporation by G. A. Paulikas, Director, Space Sciences Laboratory. Lt Randall S. Weidenheimer, YLVS, was the project officer for Mission-Oriented Investigation and Experimentation (MOIE) Programs.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SD-TR-81-106	2. GOVT ACCESSION NO. AD-A111 360	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ELECTRON DENSITIES IN A SOLAR FLARE DERIVED FROM X-RAY SPECTRA		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER TR-0082(2940-01)-1
7. AUTHOR(s) D. L. McKenzie, R. M. Broussard, P. B. Landecker, H. R. Rugge, R. M. Young, G. A. Doschek, and U. Feldman		8. CONTRACT OR GRANT NUMBER(s) F04701-81-C-0082
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Aerospace Corporation El Segundo, Calif. 90245		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Space Division Air Force Systems Command Los Angeles, Calif. 90009		12. REPORT DATE 15 January 1982
		13. NUMBER OF PAGES 19
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Sun: Coronal Density
Sun: Flares
Sun: X rays

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

We obtained high resolution solar x-ray spectra during the rising phase of a major solar flare between 0807 UT and 0905 UT on 1979 June 10. Measurements of the density sensitive line ratio, R, of the O VII $1s^2\ {}^1S_0 - 1s2s\ {}^3S_1$ (22.10 Å) flux to the O VII $1s^2\ {}^1S_0 - 1s2p\ {}^3P_1$ (21.80 Å) flux indicates that the density of the plasma at around 2×10^6 K exceeded 10^{11} cm^{-3} near the peak of the flare.

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PREFACE

We wish to thank W. T. Chater, C. K. Howey, R. L. Williams, P. A. Carranza, A. DeVito, W. Eng, K. Higa, D. A. Roux, J. H. Underwood, and D. Y. Watanabe for their contributions to the design, fabrication, and testing of the Aerospace P78-1 payload. The support of the Aerospace and Air Force Space Test Program personnel and the mission control team at the Air Force Satellite Control Facility is also appreciated.

A

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I. INTRODUCTION

The United States Air Force Space Test Program P78-1 satellite, patterned after the NASA OSO-7 satellite, carries in its sun-pointed section a set of solar x-ray experiments, including two collimated crystal spectrometers built by The Aerospace Corporation. Each spectrometer may expose either an ammonium dihydrogen phosphate (ADP; 2d = 10.64 Å) or a rubidium acid phthalate (RAP; 2d = 26.12 Å) crystal to the mechanically collimated x-ray flux. All of the crystals are on a common plate, and they are arranged so that one spectrometer obtains a spectrum using ADP while the other uses RAP. The SOLEX A spectrometer has 20 arc sec collimation and a proportional counter detector with a 5.2×10^{-3} gm-cm^{-2} beryllium window, and the SOLEX B spectrometer has 60 arc sec collimation and a channel electron multiplier array detector filtered with 1.9 μm of polypropylene with a 245 nm aluminum film. A complete instrument description is given by Landecker, McKenzie, and Rugge (1979).

On 1979 June 10 at about 0900 UT we observed a major solar flare with the RAP crystal of the SOLEX B spectrometer. Because of its small field of view and a coalignment error between the spectrometers of about 27 arc sec, the SOLEX A spectrometer made no observations of this flare. The spectra were obtained by scanning back and forth between Bragg angles of 17.4° and 61.7° (7.8 - 23 Å) at a rate of 0.525 degrees-s^{-1}. A full scan

took 84.5 sec. A line list identifying more than 100 lines observed in this flare has been compiled (McKenzie et al. 1980). This paper discusses measurements of the density sensitive O VII lines near 22 Å.

II. DENSITY-SENSITIVE HELIUM-LIKE LINE RATIOS

Gabriel and Jordan (1969) proposed that the intensity ratio, R, of the $1s^2\ ^1S_0$ - $1s2s\ ^3S_1$ forbidden line to the $1s^2\ ^1S_0$ - $1s2p\ ^3P_1$ intercombination line of the helium-like ions would be a good density diagnostic for solar plasmas. A later publication (Gabriel and Jordan 1972) modified slightly the original analysis. We will use the results from this later paper. For electron densities, n_e, below a critical value, n_e^*, the excited levels are populated from the ground state by collision, and decay by radiative transitions directly, or by cascade, to the ground state. For n_e exceeding n_e^*, collisions cause transitions of the form $2s\ ^3S \rightarrow 2p\ ^3P$, decreasing the ratio R below its low density limit. The expression relating R and n_e is given by Gabriel and Jordan (1969, 1972):

$$R = \frac{A(2\ ^3S \rightarrow 1\ ^1S)}{[n_e C(2\ ^3S \rightarrow 2\ ^3P) + \phi](1+F_3) + A(2\ ^3S \rightarrow 1\ ^1S)} \left(\frac{1+F_3}{B_3} - 1\right), \quad (1)$$

where A is the spontaneous decay rate, C is the collisional rate coefficient, ϕ is the photo-excitation rate from $2\ ^3S$ to $2\ ^3P$,

$$F_3 = \frac{C(1\ {}^1S \rightarrow 2\ {}^3S)}{C(1\ {}^1S \rightarrow 2\ {}^3P)} \quad , \qquad (2)$$

and B_3 is the effective branching ratio for $2\ {}^3P \rightarrow 1\ {}^1S$ transitions. Although its theoretical value is 0.2, F_3 is usually set equal to 0.35 so that R_0, the last term in parentheses in Equation (1), and the low-density value of R, agrees with observations. This, in effect, empirically takes cascades into account. Φ is negligible for atomic number, Z, above 6.

Following the publication of Gabriel and Jordan (1969) a number of papers appeared reporting surprisingly high densities derived from measurements of R in solar active regions or flares (e.g., Walker and Rugge 1970, Freeman et al. 1971). A number of observational difficulties render these results ambiguous. The measurement of R can be compromised by low spectral resolution (e.g., Rugge and Walker 1971) or by the presence of satellite lines resulting from innershell excitation of, or dielectronic recombination to, the lithium-like ions (Gabriel 1972, Bhalla, Gabriel, and Presnyakov 1975). To avoid ambiguity, high spectral resolution observations of a statistically significant change in R are required.

The He-like species O VII, Mg XI, and possibly Si XIII and S X.V are best suited for the determination of solar flare coronal electron densities. For N VI and C V the lines under discussion have wavelengths unreachable by high resolution

crystal spectrometers. The Ne IX intercombination line is close in wavelength to a number of Fe XIX lines that are much stronger in flares than the neon lines (McKenzie et al. 1980). The values of n_e^* for Mg XI, Si XIII, and S XV are 1.8×10^{12}, 1.3×10^{13}, and 8.9×10^{13}, respectively (Gabriel and Jordan 1972), and for higher Z species n_e^* is even larger. In addition, contamination by satellite lines increases with increasing atomic number (Bhalla, Gabriel and Presnyakov 1975). For the June 10 flare our spectra include observations of O VII and Mg XI. We see no significant change in R for Mg XI, but the data are degraded by low intensity in the intercombination line, large background fluctuations and relatively poor spectral resolution. Therefore, no conclusion regarding the plasma density can be drawn from these observations. In contrast, the O VII observations are well suited for density determinations. The RAP crystal spectrometer resolves the O VII lines very well (see Figure 1), and satellite lines are very weak for $Z = 8$. The O VII line ratios are sensitive to densities above about 7×10^9 cm^{-3}, a level expected to occur frequently in flares. Finally, the spectrometer's collimation prevented contamination of the measurement by O VII emission from solar active regions (Acton et al. 1972) or the quiet corona (McKenzie et al. 1978). In the remainder of this letter we treat the O VII observations. We are thus treating only that part of the flare plasma that emits O VII radiation; that is,

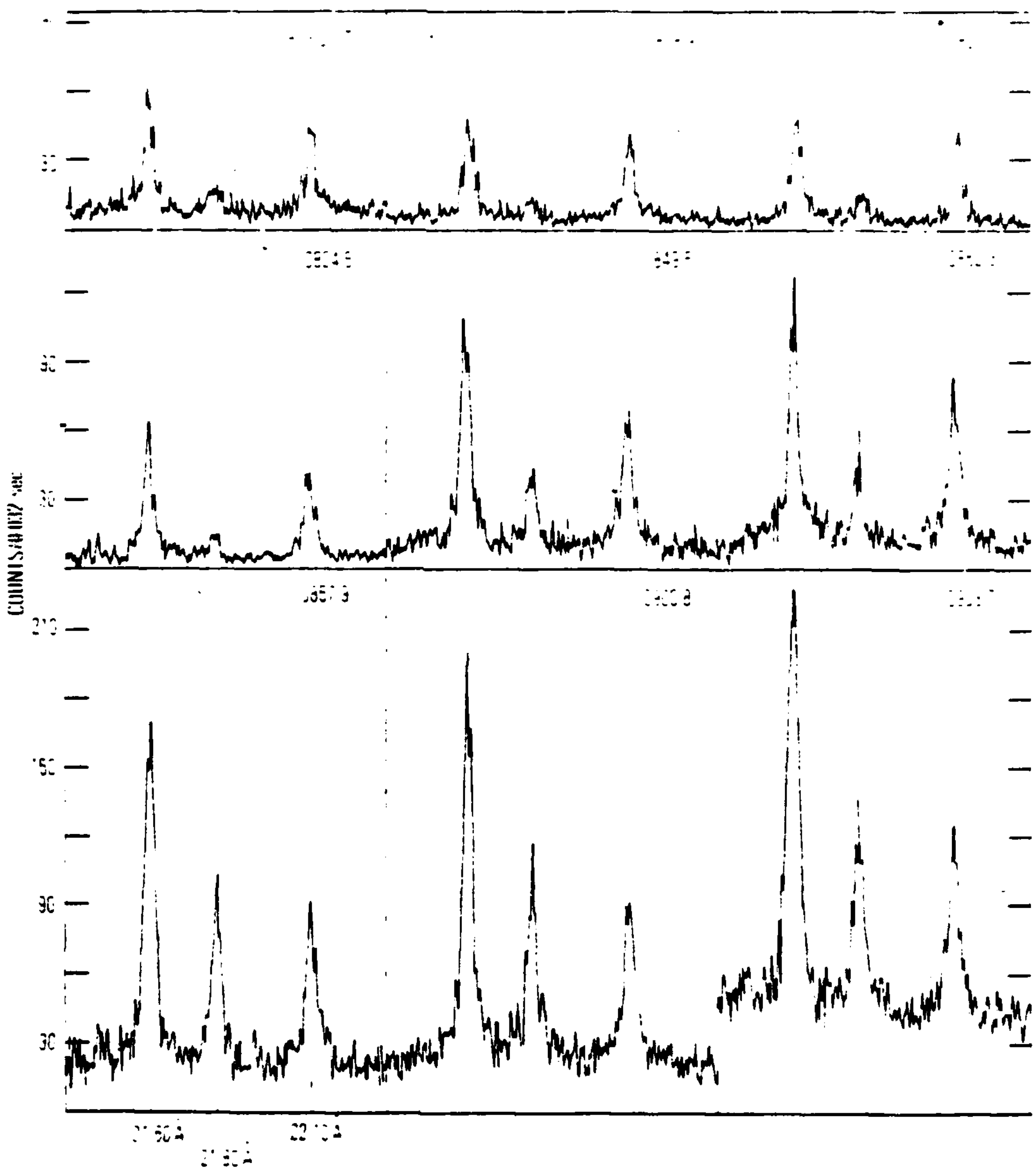

Fig. 1. The O VII line spectrum around 22 Å wavelength at various times during the flare of 1979 June 10. After 0849 UT a dramatic decrease in the ratio, R, of the forbidden (22.10 Å) to intercombination (21.80 Å) line can be seen. This is indicative of an increase in the density of the emitting plasma.

that part of the plasma having a temperature of about $1\text{-}4 \times 10^6$ K.

III. OBSERVATIONS

The June 10 flare developed in two stages over a relatively long period of time. The SOLRAD 11 x-ray detectors showed an abrupt flux increase starting at around 0805 UT. The flux then remained almost constant between 0815 and 0845 UT. The major x-ray burst started at 0845 UT, peaked at about 0905 UT and then decayed slowly. Solar Geophysical Data Prompt Reports lists a large Hα flare in McMath region 16051, starting at about 0804 UT and ending after 0900 UT. It is therefore likely that the SOLRAD x-ray flux enhancement all arose from this active region, which was the one viewed by our spectrometer. Our first x-ray spectrum, taken at around 0807 UT, showed line fluxes somewhat higher than those typical of bright active regions. Enhanced emission from Mg XII, and probably Fe XIX, indicative of temperatures higher than those usually present in nonflaring active regions, provides strong evidence that the early x-ray flux enhancement observed by SOLRAD 11 occurred at least partially in the spectrometer field of view. It is, however, possible that the brightest part of the flare was not in our field of view at any time.

Figure 1 shows sample x-ray spectra in the 22 Å region for the 10 June flare. The ratio R of the forbidden (22.10 Å) to intercombination (21.80 Å) line obviously decreases during the flare. This

indicates that as the flare progressed toward its peak intensity the O VII emission arose from a denser plasma.

Ten usable O VII spectra were recorded between 0810 and 0825 UT, during the early phase of the flare. Since all ten spectra had comparable counting rates, we use the mean obtained by simple summation to characterize R. Thus R = 3.19 ± 0.18, where the error is the standard deviation of the mean. This is somewhat lower than the empirical low-density limiting value, R_0, of 3.6 given by Gabriel and Jordan. Acton and Catura (1975) have reported experimental measurements of R in nonflaring solar regions ranging from below 3.0 to above 4.3 with a mean of 3.6, and McKenzie et al. (1978) found that R = 4.2 ± 0.2 for the solar corona outside active regions. All of these determinations are somewhat dependent upon data analysis techniques. As a check on our technique we determined R from nine nonflaring active region spectra obtained with the same spectrometer used for the June 10 observations. Summing the spectra as before we find R = 3.70 ± 0.18. Thus, although we did not actually observe a change of R from around 3.6 to 3.19, it is likely that the density exceeded n_e^* even in the early phase of the flare. When data from Gabriel and Jordan (1972) are put in Equation (1) we have

$$n_e = 6.64 \times 10^{10} \left(\frac{3.6}{R} - 1 \right) \quad cm^{-3}. \tag{3}$$

Equation (3) gives $n_e = (8.5 \pm 4.2) \times 10^9\ cm^{-3}$ for the early phase of the June 10 flare.

Conclusions regarding the density of the plasma emitting the O VII radiation during the second, and more intense, phase of the flare are not subject to such uncertainty. The dramatic change in R is obvious in Figure 1. Mewe and Schrijver (1978a, b) have done a detailed investigation of the behavior of the helium-like ions including explicitly the effects of cascades, recombination, innershell excitation and departure from ionization equilibrium on the line ratios. Departures from ionization equilibrium can produce variations in R, but with any realistic nonequilibrium flare model, a very large change can occur only for a very short time (Mewe and Schrijver 1978b). Thus the change in R observed here must indicate that the O VII lines arise from a denser plasma at the times of the later observations. Integrating the line flux and correcting for background and instrument response we find that R ranged from 2.22 ± 0.23 at 0852 UT to 0.94 ± 0.08 at 0901 UT. The corresponding density range is 4×10^{10} - $1.9 \times 10^{11}\ cm^{-3}$. Figure 2 shows the density derived from measurements of R as a function of time. The error bars are $\pm \sigma$. By using a more recent analysis of Peacock and Summers (1978) we derive densities lower than those in the figure by a factor of 1.3-2, so considerable uncertainty exists. Nevertheless we can conclude that near the flare peak the 2×10^6 K

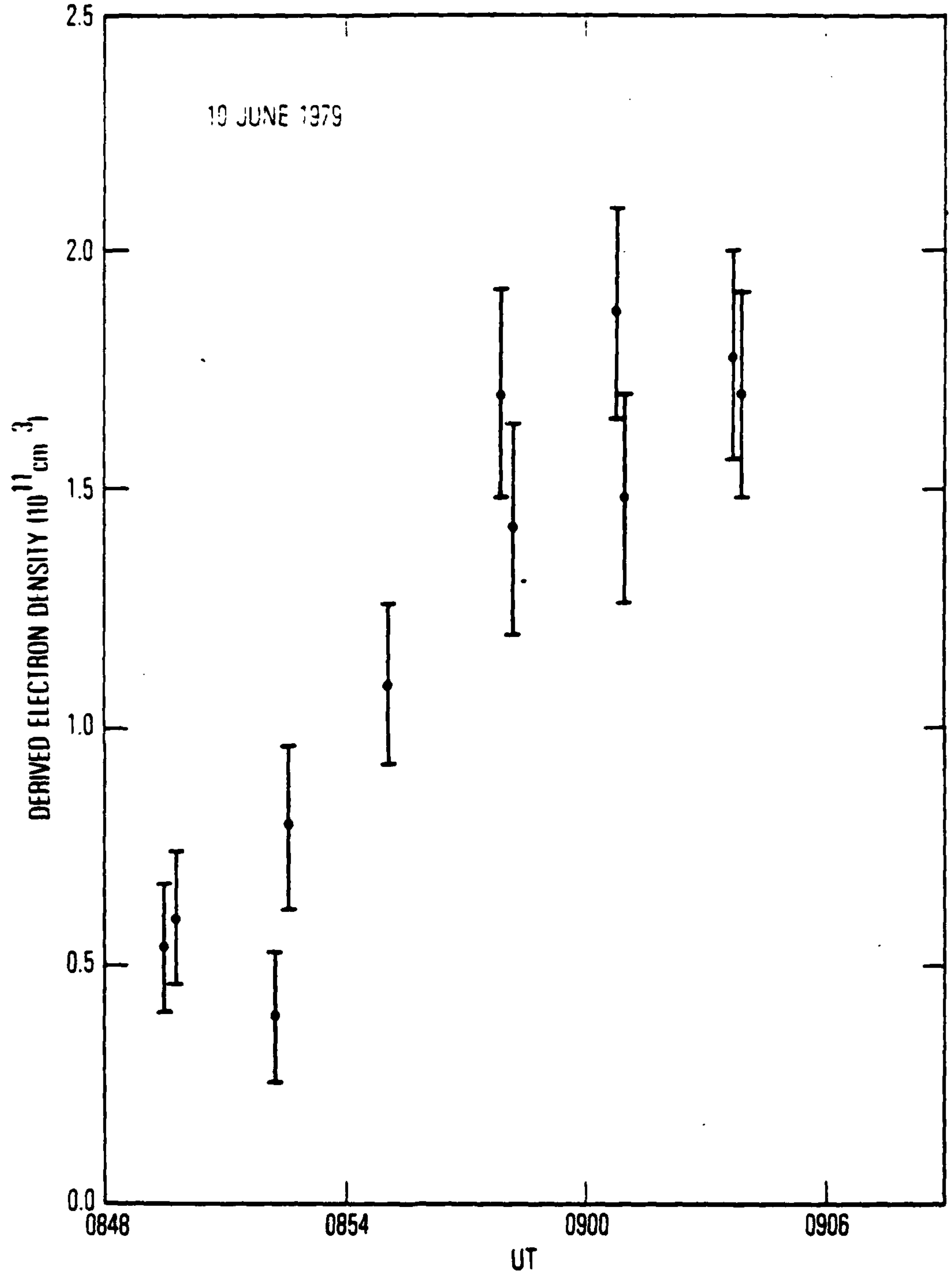

Fig. 2. The electron density of the flare plasma from which the O VII lines are emitted plotted as a function of time. Densities are derived by using the Gabriel and Jordan (1972) analysis.

flare plasma had a density exceeding 10^{11} cm^{-3}. This corresponds to an electron pressure of about 30 dyne-cm^{-2}.

The possible ways of interpreting the apparent increase in density derived here fall into two categories. First it is possible that the flaring plasma actually increased in density through a compression. Alternatively we might be observing the heating of an already dense cool plasma to a temperature of around 2×10^6 K so that O VII line radiation is emitted. For example, as time progresses, successively deeper (and denser) layers of the solar atmosphere might be heated to, and through, the temperature regime wherein O VII is abundant. In this way the O VII lines would arise from denser regions as the flare progressed. Unfortunately, for this flare, the only available density information comes from the O VII lines, and these provide data only for plasma in a limited temperature range. This information is too incomplete to allow us to distinguish a real compression from a simple heating of denser regions as time progresses.

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